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TECHNICAL REPORT NO. 81

SEPTEMBER 2, 1948

RESEARCH LABORATORY OF ELECTRONICS
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

The research reported in this document was made possible through support extended the Massachusetts Institute of Technology, Research Laboratory of Electronics, jointly by the Army Signal Corps, the Navy Department (Office of Naval Research) and the Air Force (Air Materiel Command), under Signal Corps Contract No. W36-039-sc-32037, Project No. 102B; Department of the Army Project No. 3-99-10-022.

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Abstract

To obtain suitable conductivity for direct heating, tungsten powder is added to sintered thoria cathodes. The thermionic properties of a cathode, sintered from a mixture of 67 per cent thoria and 33 per cent tungsten, were investigated. Emission constants were determined and the emission was found to be somewhat lower than that of cathodes sintered from pure thoria.

Change of cathode activity with temperature was observed and studied in detail. The cathode showed high activity at temperatures which would bring about deactivation of ordinary thoriated tungsten and decreased its activity when the temperature was lowered to the range where thoriated tungsten would be activated. A theory is proposed for the mechanism of the change in activity, involving the production of free thorium due to reduction of thoria by tungsten, diffusion and evaporation of thorium from thoria. Evaporation of thorium as well as thoria was proved by the use of a tungsten filament probe which detected evaporation of materials from the cathode by the change of its own emission. The energy of evaporation of free thorium from thoria is estimated from the experiments to be 46600 cal./g-atom. The energy of thoria is found to be 184000 cal./g-molecule. The behavior of the cathode is satisfactorily explained by the proposed theory.

THERMIONIC EMISSION FROM SINTERED CATHODES OF THORIA AND TUNGSTEN MIXTURE

1. Introduction

Sintered thoria cathodes, developed in recent years, possess a number of desirable properties,¹ of which the two most important are: 1) The ability to withstand severe punishment caused by sparking, bombardment, and other destructive phenomena. 2) Operation at higher temperatures, as compared with ordinary oxide-coated cathodes, with consequent ability to dissipate extra heating power; at the same time quite a large density of electron emission is obtainable. These properties make this type of cathode especially suitable for such applications as high-power magnetrons. Because of the extremely high resistivity of thoria, however, it is necessary to provide such cathodes with a separate heater which has to be run at very high

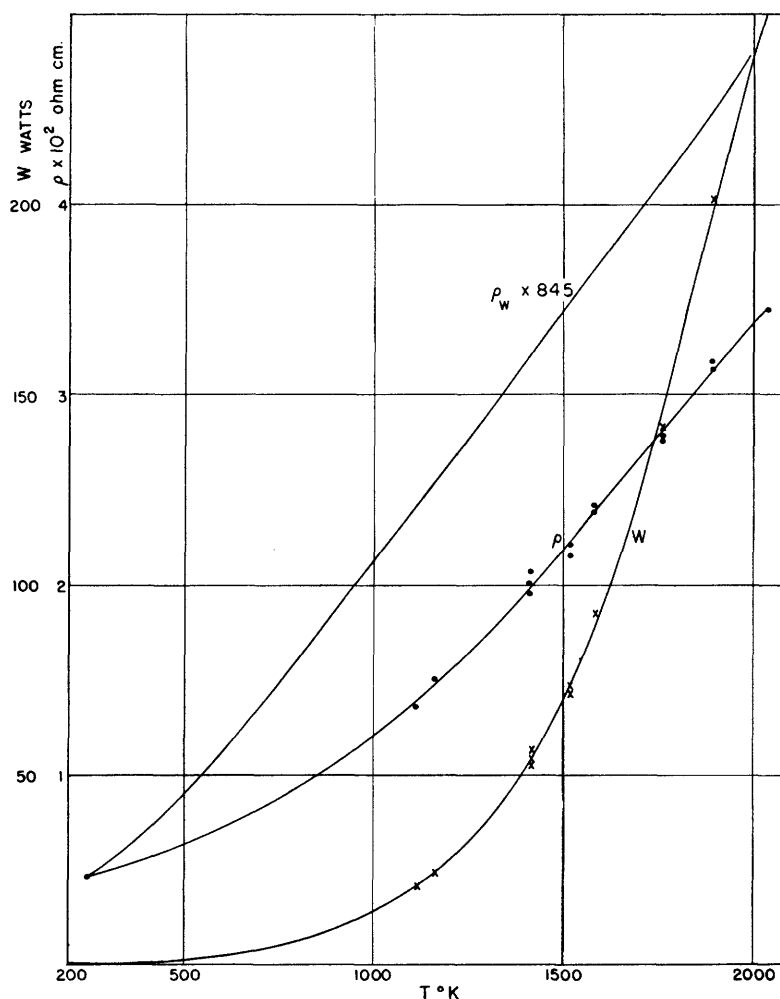


Fig. 1

1. M. A. Pomerantz, N.D.R.C. 14 Report 517, 1945.

temperatures. The design of such heaters is a problem and burn-out of the heater is frequently a source of trouble.

To simplify the problem of heating, the cathode is sintered from thorium mixed with tungsten powder. By varying the percentage of added tungsten, the resistivity of the cathode can be adjusted to a value suitable for direct heating. In this particular case the proportion is 67 per cent thorium, 33 per cent tungsten by weight. The cathode is a hollow cylinder pressed from such a mixture and fired in a hydrogen furnace at 1800°C for one-half hour. The dimensions of the cathode are: 1 in. long, 0.265 in. O.D. and 0.192 in. I.D. Molybdenum sleeves platinum-braided to the two ends serve as current leads. Figure 1 shows the resistivity ρ and the required heating power W as functions of temperature. The resistivity of tungsten ρ_w , multiplied by a factor 845 to adjust it to the same value as the resistivity of the cathode at room temperature, is shown for comparison. During the operation of over 500 hours at temperatures varying from 1100°K to 2300°K , the resistance of the cathode, as measured between the cathode leads of the tube in which the cathode is mounted, increased by approximately 10 per cent. The results of the study of the properties of such a cathode are reported here.

2. Experimental Arrangement

A diode structure is used for the study of thermionic emission (Fig. 2). The anode is a cylinder, concentric with the cathode, 1 in. in diameter and $7/16$ in. long. It is provided with guard rings, each 1 in. in diameter and $1/2$ in. long. For the measurement of true temperature, a hole, 10 mils in diameter, is drilled through the wall in the middle of the cathode. A larger hole is made in the anode so that the hole in the cathode wall can be viewed conveniently with an optical pyrometer. Before sealing off the pump, the vacuum as read by an ionization gauge was below 10^{-7} mm Hg with the cathode at a high operating temperature and with a d-c emission giving an anode dissipation several times the highest value ever reached during the operation after seal-off. The tube is also gettered. The probe arrangement shown by the dotted lines was added in a second tube only. It will be described later.

D-c emission was measured for low temperatures of the cathode. For higher temperatures a pulse modulator was used which gives pulse lengths from 0.5 to 10 μsec . The pulse current and voltage were measured on the screen of a synchroscope. The circuit is shown schematically in Fig. 2. The cathode was heated from the a-c line through a Sola constant-voltage transformer, a variac, and a high-insulation transformer in series. The last mentioned was used because the cathode was raised to high negative voltages during the pulses.

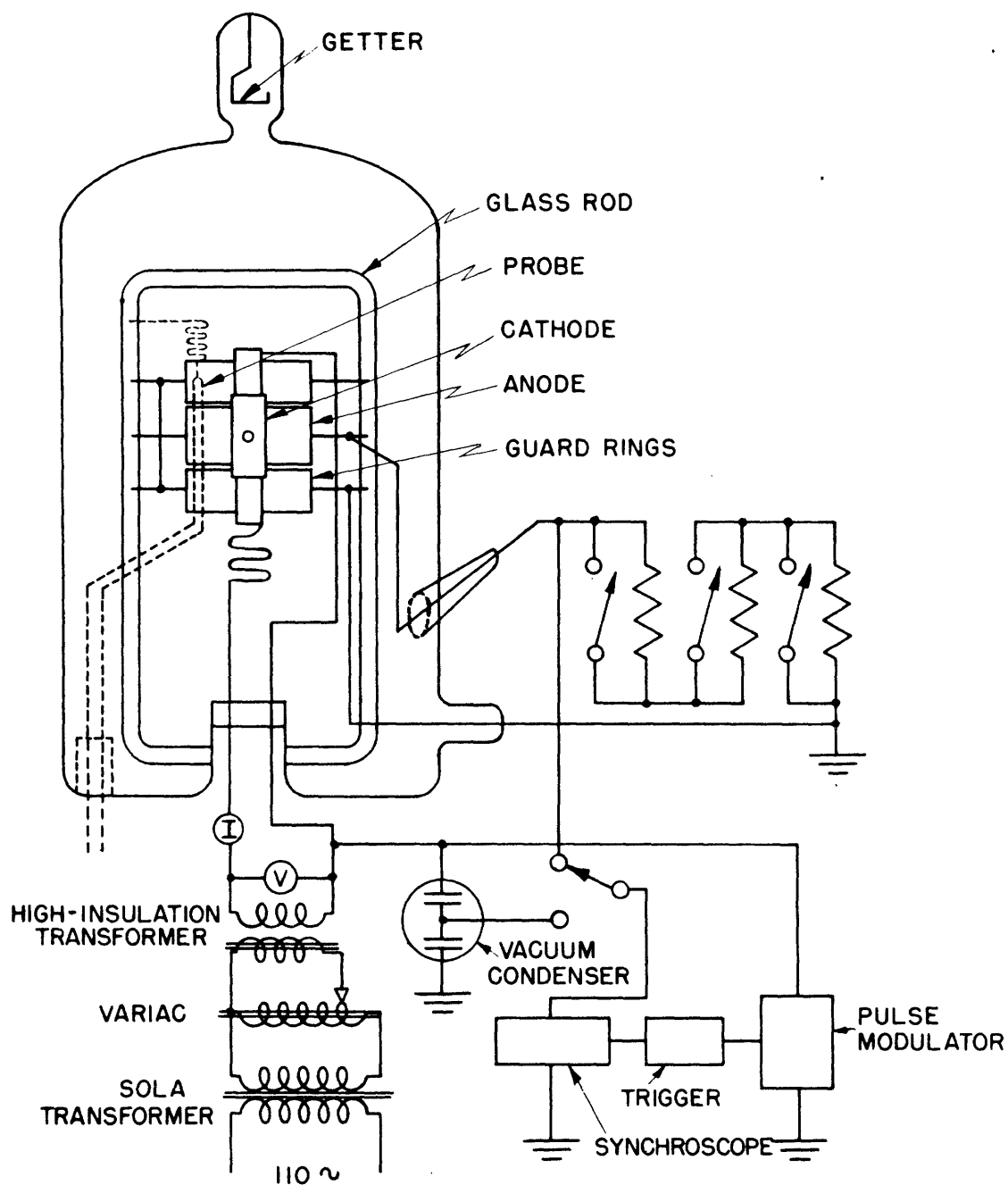


Fig. 2

3. Emission in Accelerating Fields

Figure 3 shows the curves I (multiplied by an arbitrary factor) as functions of $V^{\frac{1}{2}}$. It is seen that for sufficiently high fields the curves approach the theoretical Schottky slopes. Since the surface of the cathode consisting of thoria and tungsten mixtures is nonuniform, deviation from the theoretical slopes at low fields is expected on the basis of patch theory.¹ The fact that the curves approach the theoretical slopes more readily for

1. J. A. Becker, Rev. Mod. Phys. 7, 95, 1935.

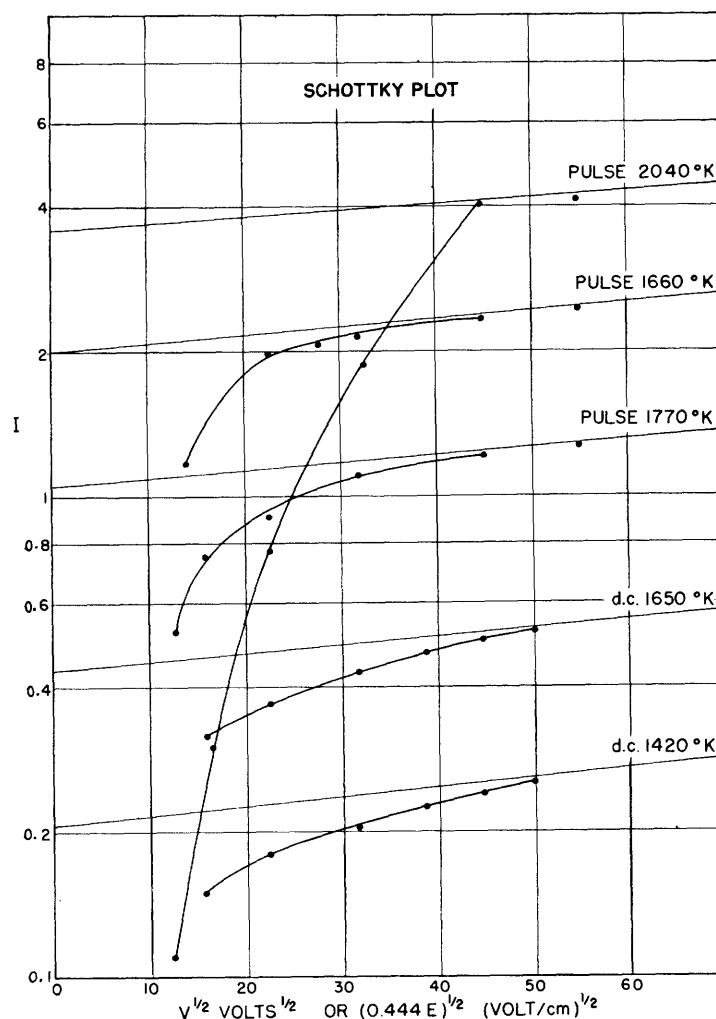


Fig. 3

higher temperatures is also consistent with the predictions of the patch theory. The sharp bending away from the theoretical line in the curve for 2040°K is the transition into space-charge-limited region; below the bend the curve follows closely the calculated 3/2 power curve.

Since the cathode is directly heated, its zero field emission cannot be readily measured. As the emission approaches Schottky lines for high voltages, we may well use the emission values at a definite, sufficiently high voltage for the determination of emission constants. All emissions were accordingly measured at 2500 volts. A still higher voltage would be preferable, as the emissions at low temperatures have not quite reached the theoretical slopes at this voltage. But we were limited in this respect by the pulse modulator. It can be seen from Fig. 3 that a higher voltage will not make a great difference.

When the cathode was kept at a definite temperature, the emission under applied d-c voltage at low temperatures and under pulse voltage at high

temperatures maintained a definite value and showed no sign of decay. For temperatures where both d-c and pulsed emission could be measured conveniently, the values were the same. This result shows that there is no fundamental difference between emission under d-c and pulsed conditions. Furthermore, the tube was opened to air and rebuilt twice. The emission properties of the cathode showed no marked change. This freedom from change is indeed one of the desirable properties of this type of cathode. If, however, the temperature was changed and maintained at a different value, the emission underwent a time change irrespective of applied voltage. This observation indicates a change of the state of the cathode with temperature. This effect will be discussed more fully later on. For determining the emission constants the cathode was maintained at a definite temperature T_0 and the emissions at different temperatures T_t 's were taken to be the initial values when the temperature was brought from T_0 to T_t . Thus all emissions corresponded to a definite state of the cathode at T_0 . Thoria being a semi-conductor, its emission equation

$$i = AT^n e^{e\phi/kT} \quad (1)$$

may have different possible values of n according to theory, depending upon the type of semi-conductor it is. Without knowing what type of semi-conductor the thoria in the cathode is, there is no basis for taking any particular value for n . We shall use the conventional value $n = 2$ for convenient comparison of the emission constants A and ϕ with data given by other authors. Figure 4 shows curves of $\log (i/T^2)$ versus $1/T$ for the two values of $T_0 = 2040^\circ\text{K}$ and $T_0 = 2320^\circ\text{K}$. Both ϕ and A are different for the cathode states at these two different temperatures. The state at 2320°K gives higher emission on account of the higher value of A .

Wright¹ gives for pure thoria cathodes prepared by different methods values of ϕ varying from 2.54 to 2.52 e.v. with A varying from 2.5 to 7.5 amp/cm²deg². Hanley² gives, for cathodetically coated pure thoria cathodes, average values: $\phi = 2.67$ e.v., $A = 2.63$ amp/cm²deg² under d-c conditions and $\phi = 2.55$ e.v., $A = 5.62$ amp/cm²deg² under pulsed conditions. Our values of ϕ are higher than those given by these authors. This result may be due to the fact that a part of the surface of our cathode is presented by tungsten which has a high work function. Dependence of emission constants on the cathode temperature was also observed by Weinreich³ for thoria coated on tungsten. Contrary to our results the constant A remains the same while the work function is lower for a higher temperature of the cathode.

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1. D. A. Wright, Nature 160, 129, 1947.
 2. T. E. Hanley, J. App. Phys. 19, 583, 1948.
 3. M. O. Weinreich, Rev. Gen. Elec. 54, 243, 1945.

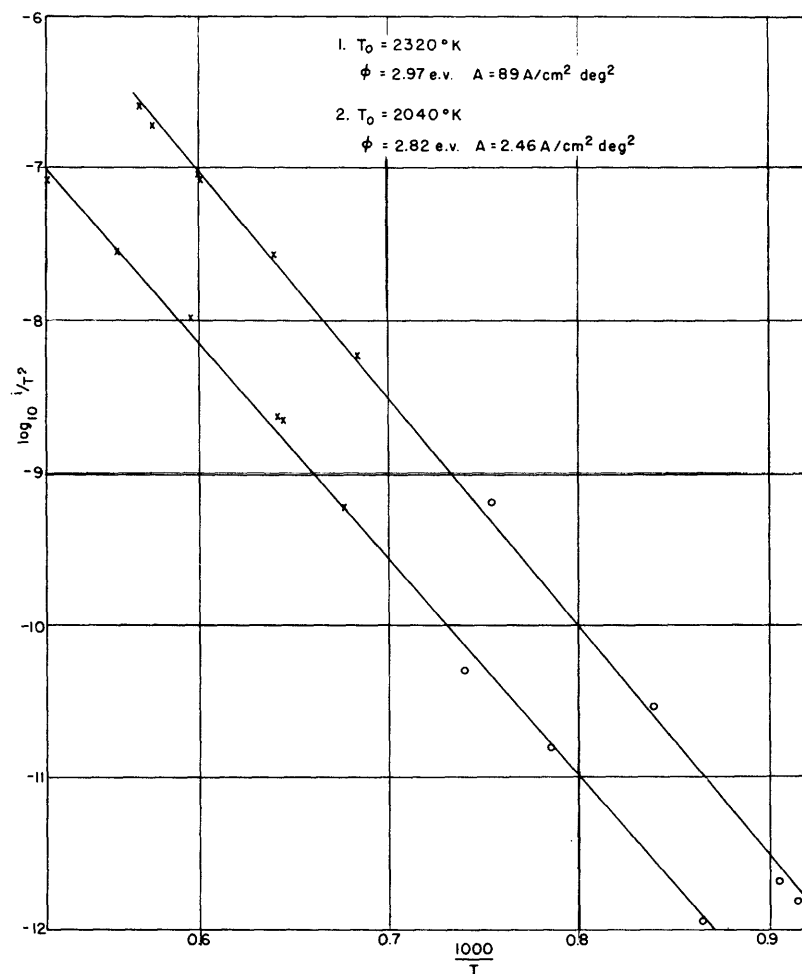


Fig. 4

4. Temperature Dependence of Activity

It has been mentioned that the cathode activity shows temperature dependence. In fact the emission constants have different values for different conditioning temperatures of the cathode. The observations on this effect will now be given in detail. If the cathode was kept at a temperature T_1 until its emission had reached a steady value and then brought down to a lower temperature T_2 , the emission tested intermittently at T_2 changed with time. If the temperature was again restored to T_1 , the emission would build up gradually to its original equilibrium value. The process could then be repeated. This reversible change is shown in Fig. 5 for $T_1 = 2040^\circ\text{K}$ and $T_2 = 1670^\circ\text{K}$. It must be emphasized that the anode voltage was applied only when a point was taken and only long enough for the measurement to be made. This is, therefore, an entirely different phenomenon from the decay of emission

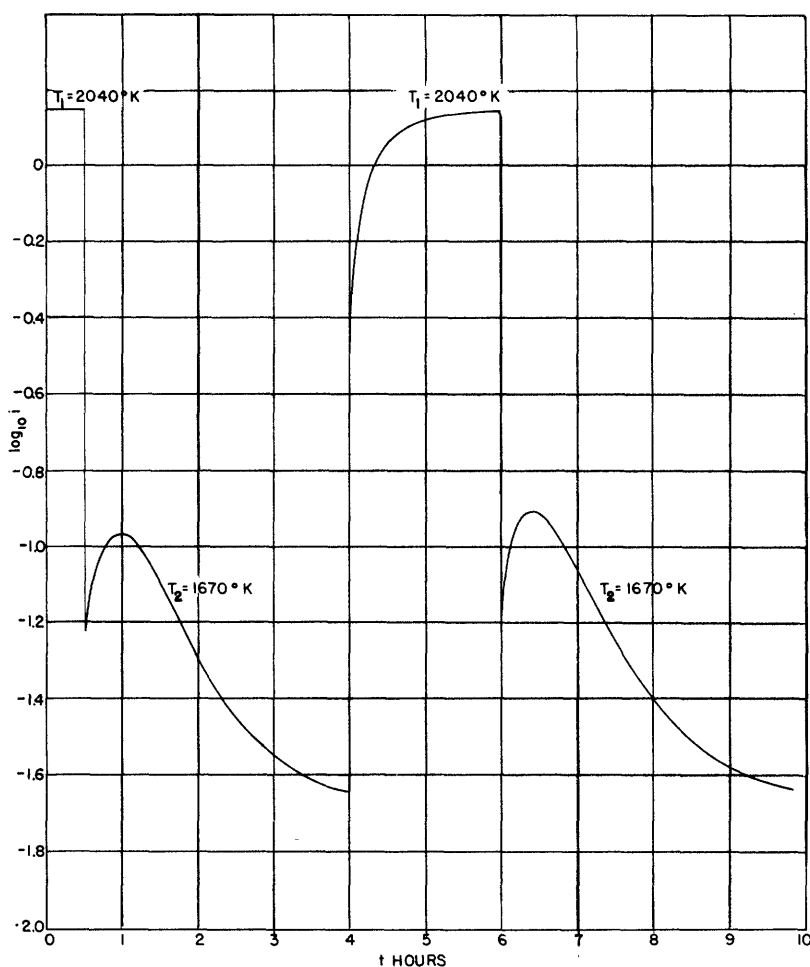


Fig. 5

under applied voltage observed for oxide-coated cathodes. Figure 6 shows the good reproducibility of such curves taken at $T_2 \sim 1670^\circ\text{K}$ for two values of T_1 : 2320°K and 2040°K . Curves taken many days apart, during which time the cathode was subjected to different operating conditions, would check each other if only the cathode was initially brought to equilibrium conditions at the same T_1 . This fact indicates that it was not the effect of residual gases in the tube. In a gettered tube gas effect cannot be expected to show such good reproducibility. Furthermore, it was found that such a curve could be interrupted for a long time, overnight, with the cathode cold; the emission would start again at the same value where the curve was interrupted and keep on changing in the same way as if there had been no interruption. Curves were taken at different T_2 values ranging from 1200°K to 1920°K for the same two values of T_1 . Figures 7 and 8 give the curves for two other values of T_2 . They show the same behavior. Comparing Figs. 6, 7, and 8 we see that with decreasing temperature the rate of change

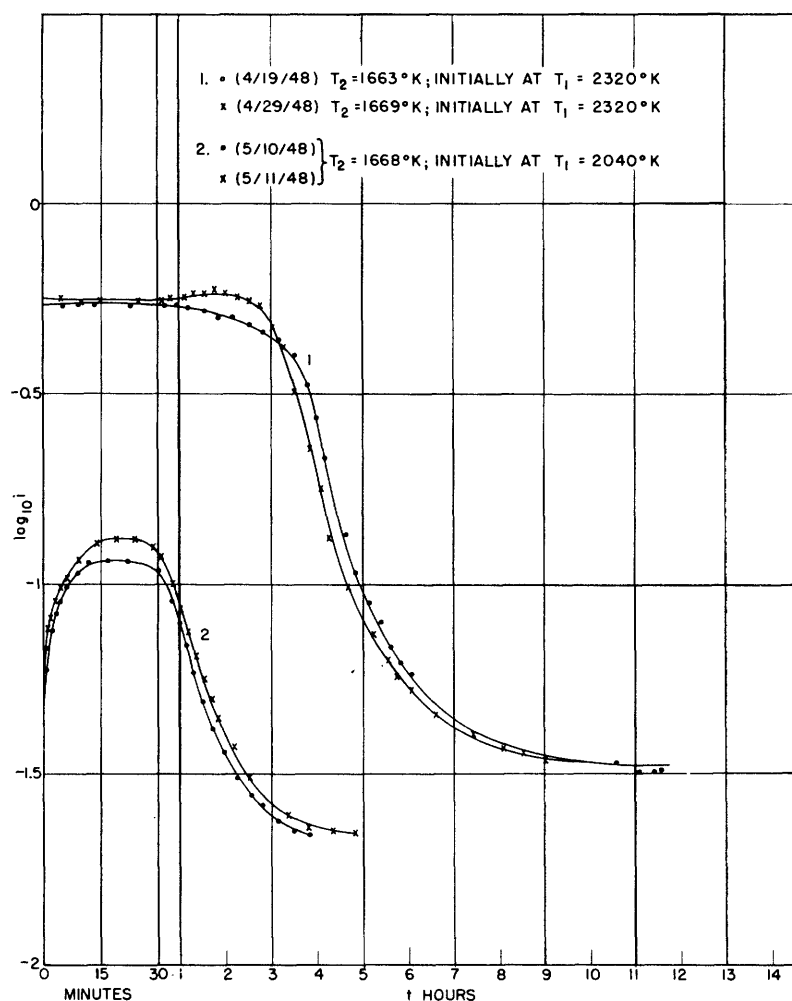


Fig. 6

of emission decreases. All curves for $T_1 = 2040^\circ\text{K}$ show initial rise, whereas for $T_1 = 2340^\circ\text{K}$ they start off rather flat. Generally for the test temperature range 1200°K to 1920°K curves are similar in character. At very low testing temperatures, $T_2 = 1210^\circ\text{K}$, the initial rise in curves for $T_1 = 2040^\circ\text{K}$ could still be observed. The emission rose in 6 or 7 hours to a rather steady value, thereafter changed little in the course of 24 hours. The drop in emission observed at higher T_2 had either disappeared or proceeded at a very slow rate.

To follow the change in emission constants data for curves of $\log(1/T^2)$ vs. $1/T$ were taken quickly at four points A, B, C, and D of the run shown by Curve 2, Fig. 8. These curves and the values of emission constants they yield are given in Fig. 9. They show that both ϕ and A underwent changes.

In a cathode with thoria and tungsten present together such reversible and reproducible changes of activity can naturally be ascribed to the production, diffusion, and evaporation of free thorium. The effect of free

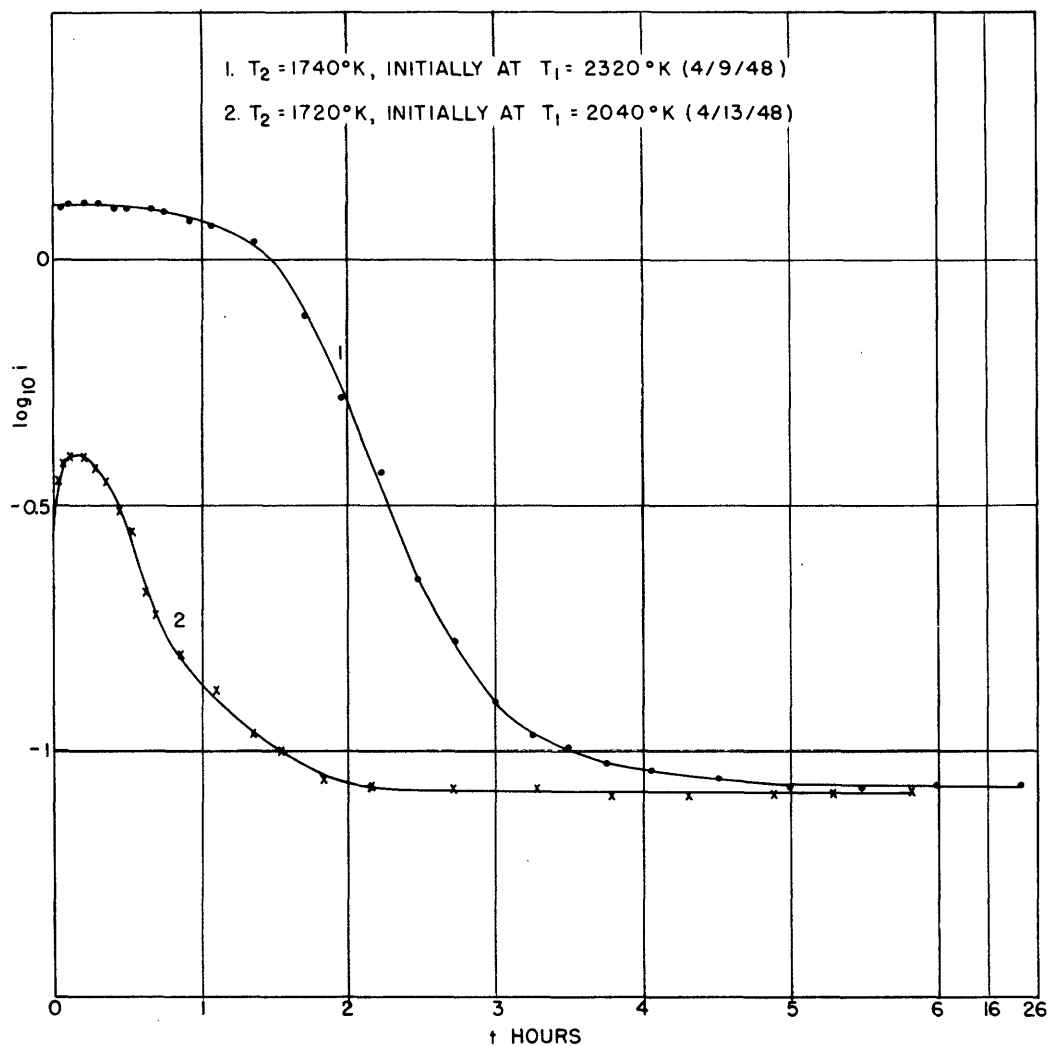


Fig. 7

thorium on the activity can be either a bulk effect or a surface effect. When dispersed inside thoria crystals, free thorium may change ϕ and A of thoria as impurities in a semiconductor. It may also change ϕ and A by being adsorbed on the surface of the cathode. It may be argued that free thorium must be produced during the operation of the cathode, since if we have only a fixed amount of thorium as produced in the cathode originally during its fabrication, then without evaporation an equilibrium condition should soon be established and there would then be no changes of activity. Evaporation should cause irreversible changes in the activity which are not observed.

The results of the following experiment, shown in Fig. 10, are significant for understanding the mechanism of the change of activity. After the emission reached a steady value at $T_1 = 2040^\circ\text{K}$, the temperature of the cathode was lowered to $T_2 = 1670^\circ\text{K}$ and changes of emission with time were observed. After an interval of time the cathode temperature was

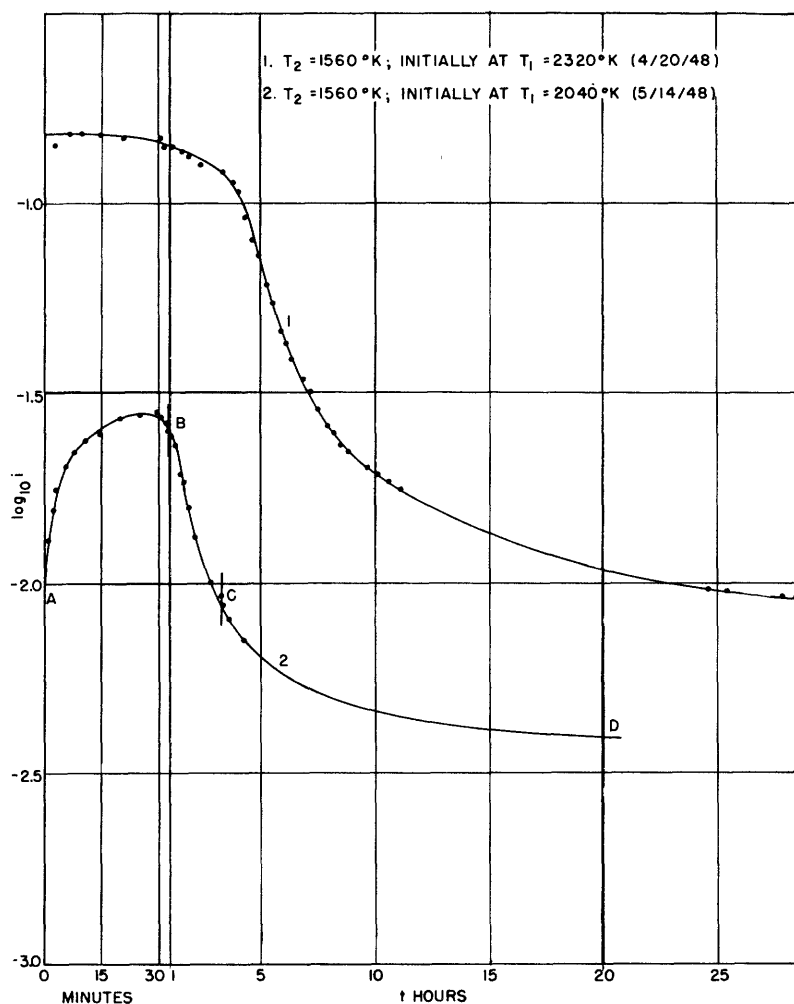


Fig. 8

increased to T_1 for a very short time and brought back to T_2 again. In one of the curves the short time elevation to T_1 was made at the time when the emission at 1670°K had reached its peak. In the second curve this was made when the emission at 1670°K had decreased to a much lower value. In both cases immediately after the short time at the higher temperature, 2040°K , the emission was greatly reduced, then recovered partially. Whereas keeping the cathode at T_1 for a long time would start the curve all over again from the beginning, raising the temperature to T_1 for a short time made the emission drop sharply and failed to head the curves back toward the beginning. In other words, the activity of the cathode can be decreased very quickly whereas the complete adjustment of the state of the cathode is much more sluggish.

In the light of all the experiments we have arrived at the following picture of the mechanism of the cathode: 1) The variation of the activity is caused mainly by the variation of the amount of free thorium adsorbed on the surface. 2) Free thorium is produced through reduction of thorium by

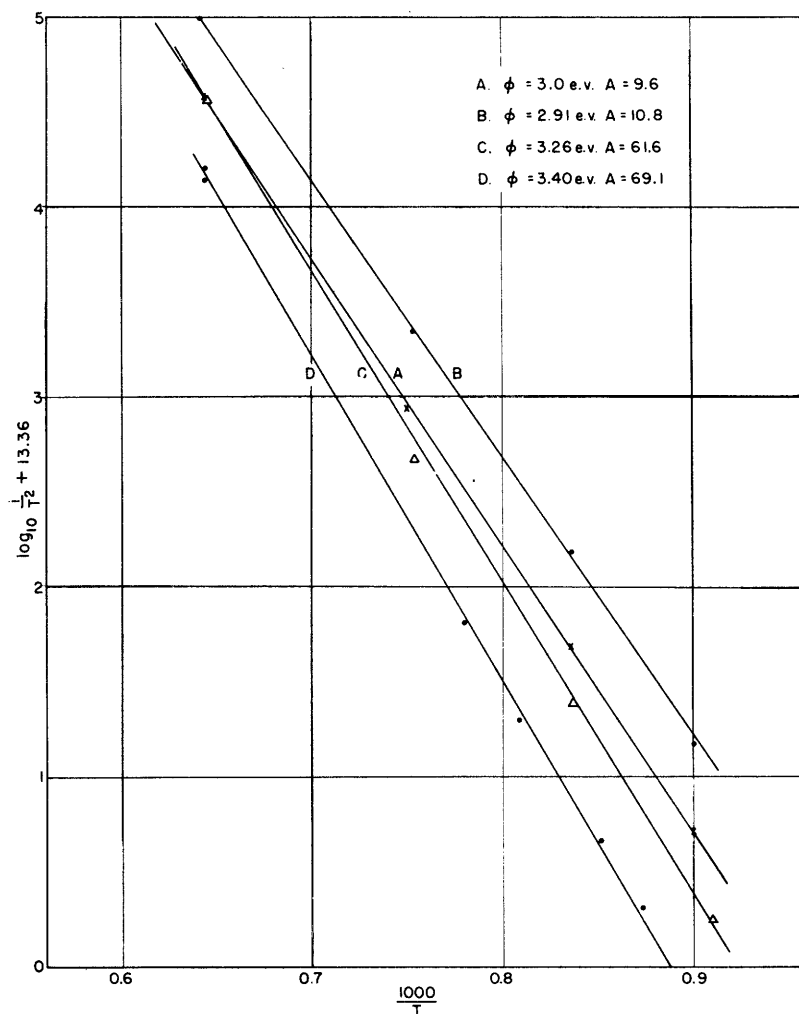


Fig. 9

tungsten throughout the cathode. 3) Heat of reduction of thorium by tungsten is higher than the heat of evaporation of thorium from the cathode which is in turn higher than the heat of diffusion of thorium in the cathode.

This hypothesis can well explain the results shown in Fig. 10. As the concentration of thorium takes time to change when the temperature of the cathode is suddenly raised, the amount of adsorbed thorium will at first decrease on account of more rapid increase in evaporation with temperature as compared with diffusion. As a result raising the temperature for a short time has the effect of decreasing the emission. The increased rate of thorium production, however, more than compensates the increased rate of evaporation since the heat of thorium reduction is assumed to be greater than the heat of evaporation of thorium. Therefore, if the cathode is held at the higher temperature, eventually a higher thorium concentration will be built up which in equilibrium supports a larger number of thorium atoms adsorbed on the surface. If now the temperature is lowered the curves will start again from the

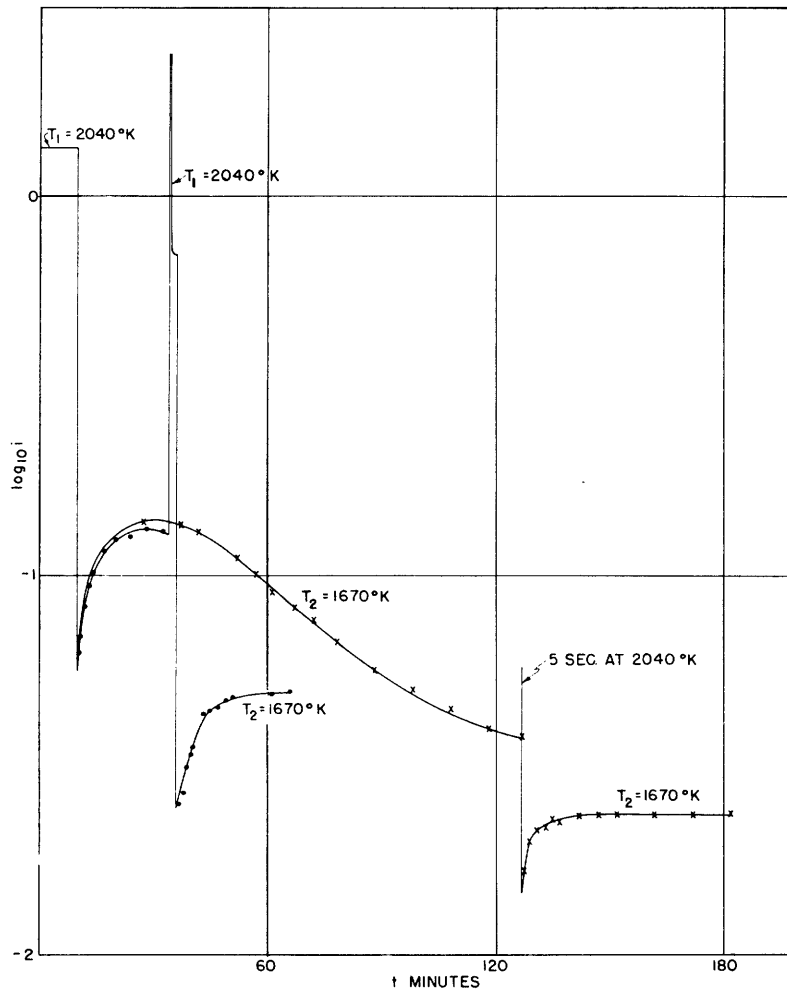


Fig. 10

beginning. The assumption, that heat of reduction of thorium is larger than the heat of evaporation of thorium, explains the increase of equilibrium activity with increasing temperature as shown by Figs. 6, 7, and 8. The initial emission of each curve corresponds to the equilibrium activity at the higher initial temperature T_1 and the final emission, which is lower, corresponds to the equilibrium activity at the lower temperature T_2 at which the emission is tested. Also Fig. 6 shows that the activity at 2320°K is higher than at 2040°K .

On the basis of this hypothesis, if the temperature is brought down from a higher value T_1 to a lower value T_2 , the emission should at first increase on account of more rapid decrease of evaporation with temperatures than diffusion. On account of still more rapid decrease of reduction of thorium, the thorium concentration becomes depleted and eventually the emission will decrease to a lower than initial value. Curves (2), Figs. 7 and 8, actually show this type of behavior. The fact that Curves (1) in the same

figures do not show initial rise in emission we assume to indicate that at $T_1 = 2320^\circ\text{K}$ the amount of adsorbed thorium is close to a full monolayer.

Although in thoriated-tungsten filaments considerable production of thorium takes place at temperatures higher than the temperatures reached by our cathode, the production should be much more rapid in our cathode than in a thoriated-tungsten filament at the same temperature. Whereas a thoriated-tungsten filament contains about 1 per cent thoria, our cathode is a mixture of 33 per cent tungsten and 77 per cent thoria.

The evaporation of thorium from tungsten is very slow at the temperatures at which changes of activity of our cathode were observed as shown by Figs. 6, 7, and 8. Also the heat of evaporation of thorium from tungsten is higher than the heat of reduction of thoria. But in our case thorium may be evaporated from surfaces of thoria rather than from tungsten. The data on thoriated tungsten do not necessarily contradict our hypothesis. To substantiate our hypothesis, however, an independent proof of evaporation of thorium during the change of cathode activity is desirable. The following experiment was made for this purpose.

5. Probe Measurement

The tube was rebuilt with the same cathode. The structure is the same as described previously except for the addition of a probe. Its arrangement is shown by the dotted lines in Fig. 2. It is a hairpin filament of 10-mil tungsten wire. Its temperature is calculated from the heating current and its emission measured at 1390°K , 1550°K , and 1760°K checks with the calculated values. It serves to detect evaporation of materials from the cathode, which condensing on it change its emission. Its emission could always be brought back to normal values by flashing it at 2460°K for a sufficient period of time. A few seconds of flashing was enough to bring the emission almost back to normal values. Sometimes it was found necessary to keep the probe at the flashing temperature for many minutes before its emission at the low testing temperature, 1390°K , was quite restored to its normal value. This result may be ascribed to material deposited on the tips of the lead wires, and other relatively cool portions of the structure. Consequently this material may not have been completely removed by a short flashing procedure and could diffuse back to the emitting portion of the filament. In testing the probe emission, the cathode, the anode, and the guard rings were tied together to serve as the anode. The emission was measured with a galvanometer, the sensitivity of which was 4.4×10^{-10} amp/mm.

6. Evaporation of Thorium

When the cathode had been brought to equilibrium at $T=1770^\circ\text{K}$, it was found that after glowing the cathode for six hours at this temperature, the

emission of the probe did not change appreciably from its normal values. If the cathode had been previously heated at $T = 2220^{\circ}\text{K}$ for 12 minutes, then after glowing the cathode at 1770°K for two hours, the probe gave an emission at 1250°K which is over 20,000 times the calculated normal emission at this temperature. During this experiment the probe was kept at 2460°K for 8 minutes more after the cathode had been cooled down to room temperature. Its emission was then tested and found to be normal. The cathode was then glowed for two hours at 1770°K . The experiments prove conclusively that the increase of probe emission in the second case was due to free thorium evaporated from the cathode. The only other material that could come from the cathode to enhance the probe emission is thoria itself. But the evaporation of thoria depends upon the cathode temperature only and should not show such decided dependence on the previous history. These results show definitely that considerable reduction of thoria takes place at 2220°K building up a concentration of free thorium which keeps evaporating at 1770°K . They also show that reduction of thoria in the cathode at 1770°K must be very slow. This is direct evidence of the correctness of the basis for our theory about the change of cathode activity.

Figure 11 shows the probe emission at 1250°K as a function of the time interval of glowing the cathode. Points taken for four different glowing temperatures of the cathode can be fitted by a single curve which is shifted horizontally a suitable distance for each cathode temperature. From these curves we get the relative lengths of time necessary to glow the cathode at the different temperatures to obtain a certain value of probe emission. This, $1/t_0$, is the relative rate of thorium evaporation.

We have another way of estimating the rate of thorium evaporation. When the cathode is not in a state of equilibrium, the rate of change of N , the number of adsorbed thorium atoms per cm^2 of the surface, is determined on one hand by the rate of thorium diffusion onto the surface and on the other hand by its rate of evaporation from the surface. The diffusion rate is given by DG , where D is the diffusion and G is the concentration gradient at the surface. We assume that the rate of evaporation is proportional to the number of adsorbed atoms. Thus we have:

$$\frac{dN}{dt} = DG - EN. \quad (2)$$

Both D and the coefficient for evaporation E are functions of temperature. Usually an exponential function can be assumed for each of them:

$$\left. \begin{aligned} D &= D_0 e^{-E_d/kT} \\ E &= E_0 e^{-E_e/kT} \end{aligned} \right\} \quad (3)$$

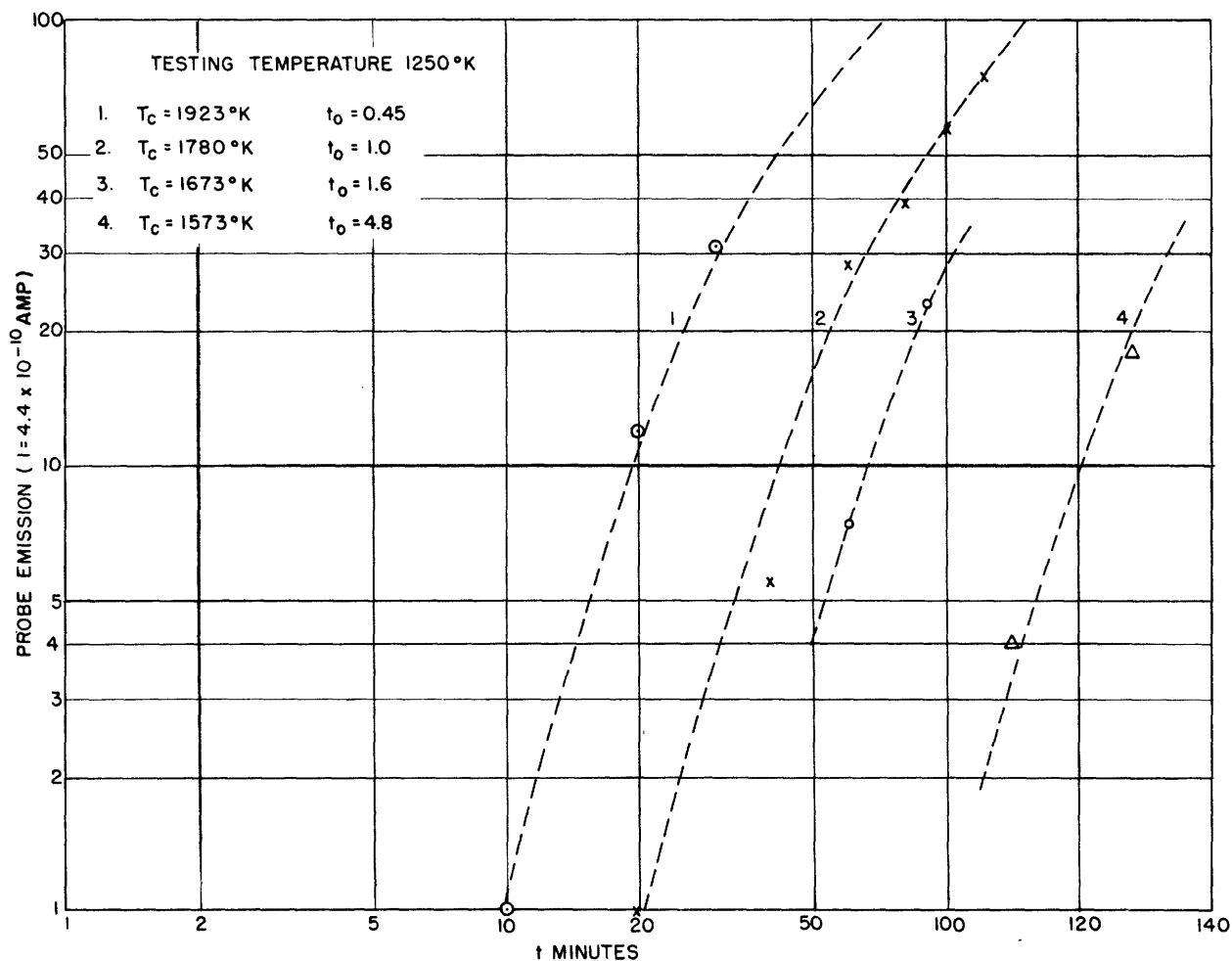


Fig. 11

In the case of thorium adsorbed on tungsten it has been shown that~

$$\log \frac{1}{i_c} = L \cdot \frac{N}{N_c} \quad (4)$$

where N_c is the number of adsorbed thorium atoms/cm² when the surface is completely covered, i and i_c are the emission currents corresponding to N and N_c , respectively. The factor L depends on N but may be taken as constant for limited ranges of $\frac{N}{N_c}$. By analogy we shall assume

$$\log i \propto (N + \text{const}). \quad (5)$$

When the cathode is brought to equilibrium at a temperature T_1 , definite G_1 and N_1 are established, determined by the rates of production, diffusion, and evaporation. If the temperature is suddenly lowered to T_2 , at

I. W. H. Brattain and J. A. Becker, Phys. Rev. 43, 428, 1933.

which reduction of thorium becomes negligible, N and i may increase at first on account of smaller energy of diffusion and consequent less slowing down of diffusion than evaporation. If the cathode is kept at T_2 , the concentration of thorium becomes depleted with time as a result of continuous evaporation and little fresh production. Eventually G becomes small and the evaporation term in Eq. (2) becomes predominant over the diffusion term and we have

$$\frac{dN}{dt} \propto -EN, \quad (6)$$

the solution of which is

$$N \propto e^{-Et}. \quad (7)$$

In view of Eq. (5), we have then

$$\frac{d(\log i)}{dt} = \frac{dN}{dt} \propto e^{-Et} \quad (8)$$

and

$$\log \frac{d(\log i)}{dt} = \text{const} - Et. \quad (9)$$

The factor $\frac{d(\log i)}{dt}$ is the slope of experimental curves such as shown in Figs. 6, 7, and 8. If our assumption is correct, then the logarithm of this factor plotted against t should become a straight line with slope E after the cathode had been kept at T_2 for sufficient time to have the thorium concentration depleted enough for the evaporation to predominate. Figure 12 gives such plots for $T_2 = 1668^\circ\text{K}$ and two different original temperatures: $T_1 = 2320^\circ\text{K}$ and $T_1 = 2040^\circ\text{K}$. They are calculated from the experimental curves of Fig. 7. When the experimental curves begin to fall quickly, these plots do become straight lines. According to our theory the slope of this straight portion being equal to E should be determined by T_2 independent of T_1 .

Figure 13 gives $\log E$ plotted against $1/T$. Also plotted is the logarithm of $1/t_0$ from Fig. 11, which was obtained from probe measurements and is the relative measure of evaporation at different temperatures. All these points should fall on a straight line according to Eq. (3). The points are rather scattered. The straight line drawn to fit these points is expressed by the equation

$$\log_{10} E = \text{const} + \frac{10200}{T} \quad (10)$$

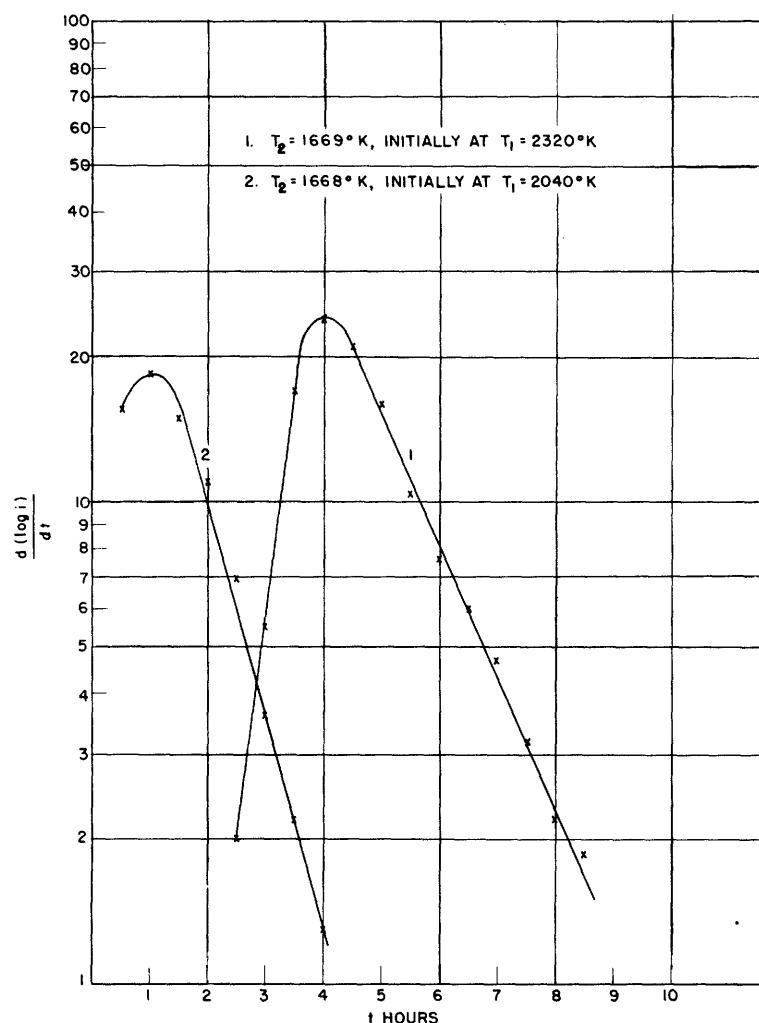


Fig. 12

The slope of this line multiplied by 4.575 gives the heat of evaporation to be 46600 cal/g-atom. Although this slope is not determined very accurately because of the scattering of the points, it serves to indicate the order of magnitude. In view of the fact that the points were obtained from experiments made many days apart and the probe experiments were made with a new tube, the scattering may be considered not too bad. The fact that $\log(1/t_0)$ and $\log E$ derived from different experiments fall approximately on the same line lends support to our theory. That the heat of evaporation obtained is much lower than the value for evaporation of thorium from tungsten¹ (4.575×44500 cal/g-atom) indicates that thorium is evaporated from the surface of thoria.

1. I. Langmuir, Phys. Rev. 22, 357, 1923.

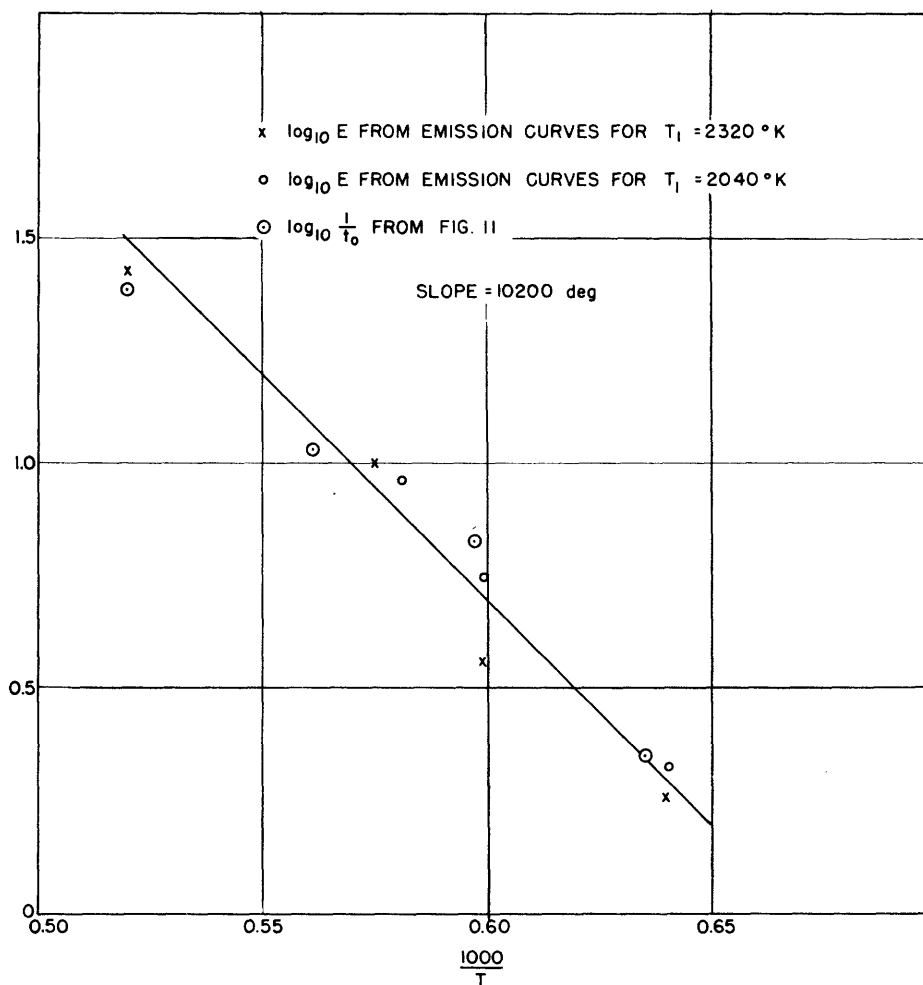


Fig. 13

7. Evaporation of Thoria

At cathode temperatures above 1900°K the following phenomena were observed in the probe emission. After the cathode had been glowed for a certain period of time, the probe emission measured at 1390°K was above its normal value. When the probe temperature was raised to 1550°K the emission decayed fairly quickly and occasionally dropped below the normal emission. But flashing for a few seconds at 1970°K made the emission tested at 1390°K rise again. With successive flashing, the emission went through a peak then fell, approaching its normal value. This behavior is shown in Fig. 14. The measurements were taken after the cathode was glowed at 2130°K for 5 minutes with the probe unheated.

The fall of emission at 1550°K is apparently due to rearrangement by diffusion of materials deposited on the probe. The rise of the emission during the flashing of the probe we assume to be due to reduction of thoria deposited on the probe from the cathode. Figure 15 shows the probe emission, measured at 1390°K while the probe was flashed at 1970°K , after the cathode had been glowed for different lengths of time at 2030°K . The bottom

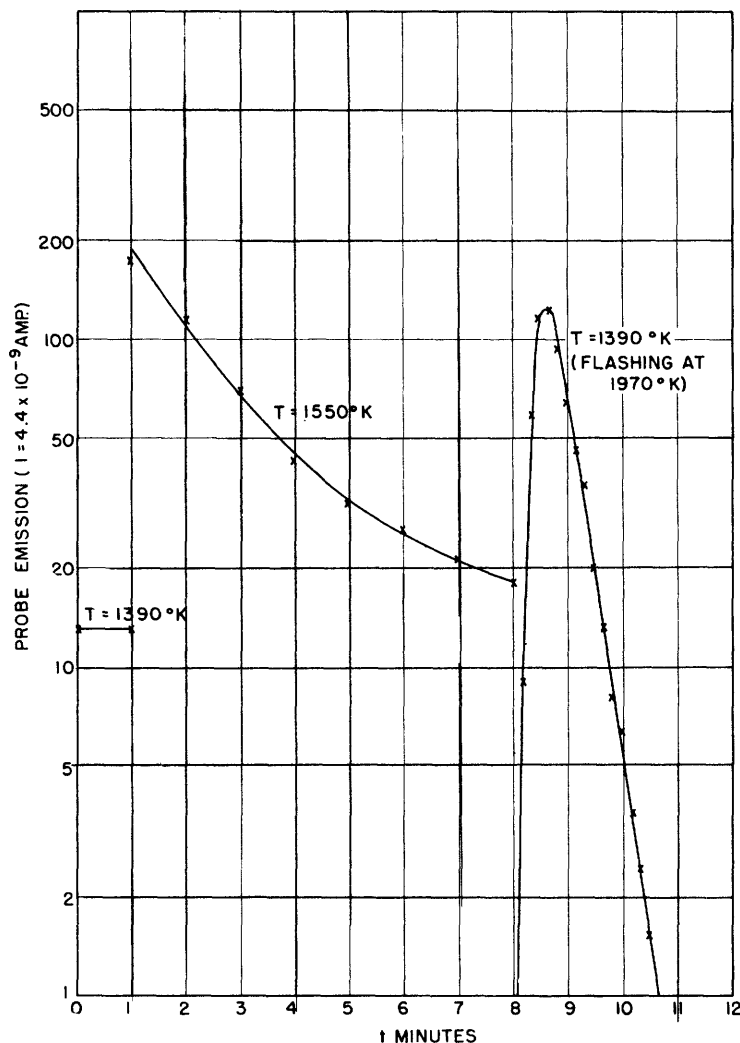


Fig. 14

line corresponds to about ten times the normal emission. The time required for the emission to fall to this value is seen to be approximately proportional to the time for which the cathode had been glowed. The same result was observed at 2230°K, 2130°K, and 1940°K. We take this time as a measure of the amount of thorium deposited on the probe. Below the value of about ten times the normal emission the curves became irregular. Materials deposited on the ends of the filament may be the cause of this irregularity. With this measure of the amount of deposited thorium we can compute from data taken for different temperatures T of the cathode (curves similar to those shown in Fig. 15) the time, t_e , required for glowing the cathode to deposit a certain amount of thorium on the probe. Figure 16 shows the straight line relation between $\log_{10} t_e$ and $1/T$. The equation of this line is:

$$\log_{10} t_e = \text{const.} - \frac{39400}{T} \quad (11)$$

The heat of evaporation of thorium is thus 184000 cal/g-molecule.

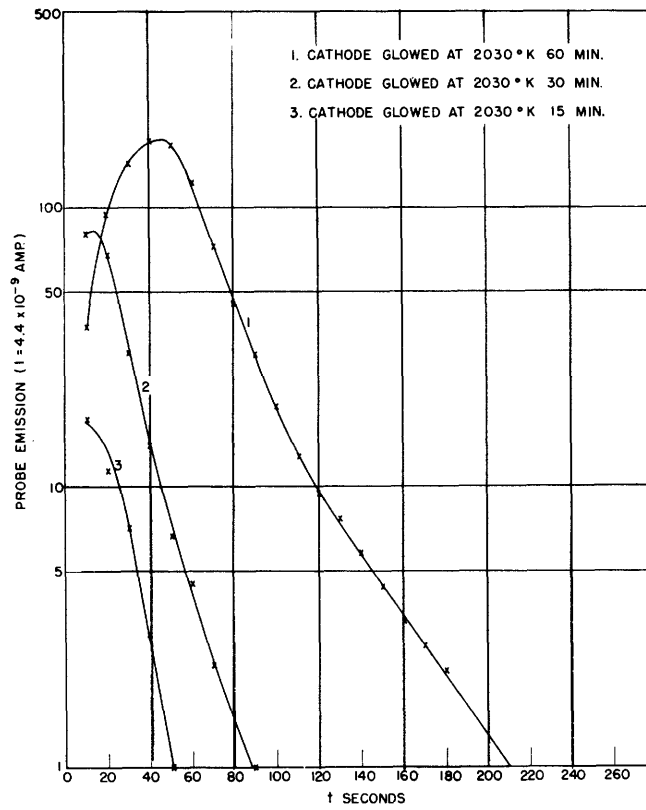


Fig. 15

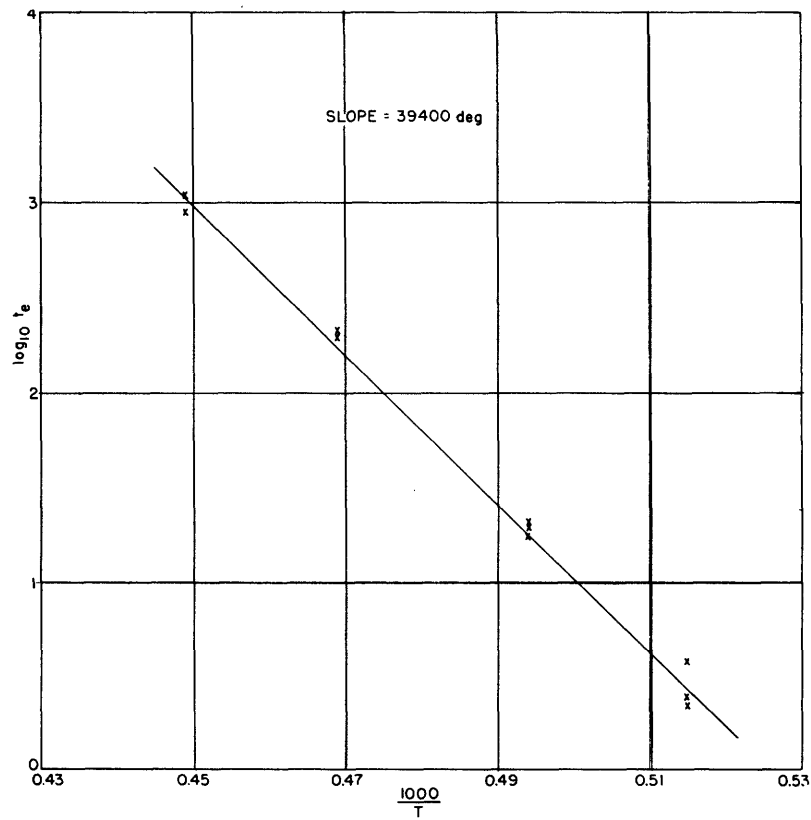


Fig. 16

8. Diffusion of Thorium

Equations (2) and (5) give:

$$\frac{d(\log i)}{dt} \propto DG - EN.$$

By allowing the cathode to come to equilibrium at a fixed temperature T_1 we established the same values of G and N . The initial values, $\left. \frac{d(\log i)}{dt} \right|_{t=0}$, when the cathode is brought down from T_1 to different temperatures, should then be a combination of two exponential functions of $1/T$ determined by D and E , according to Eq. (3). Figure 17 gives the curve $\log \left. \frac{d(\log i)}{dt} \right|_{t=0}$ versus $1/T$ for $T_1 = 2040^\circ\text{K}$. These data are taken from curves similar to Curves 2 of Figs. 6, 7, and 8. For temperatures below 1700°K the

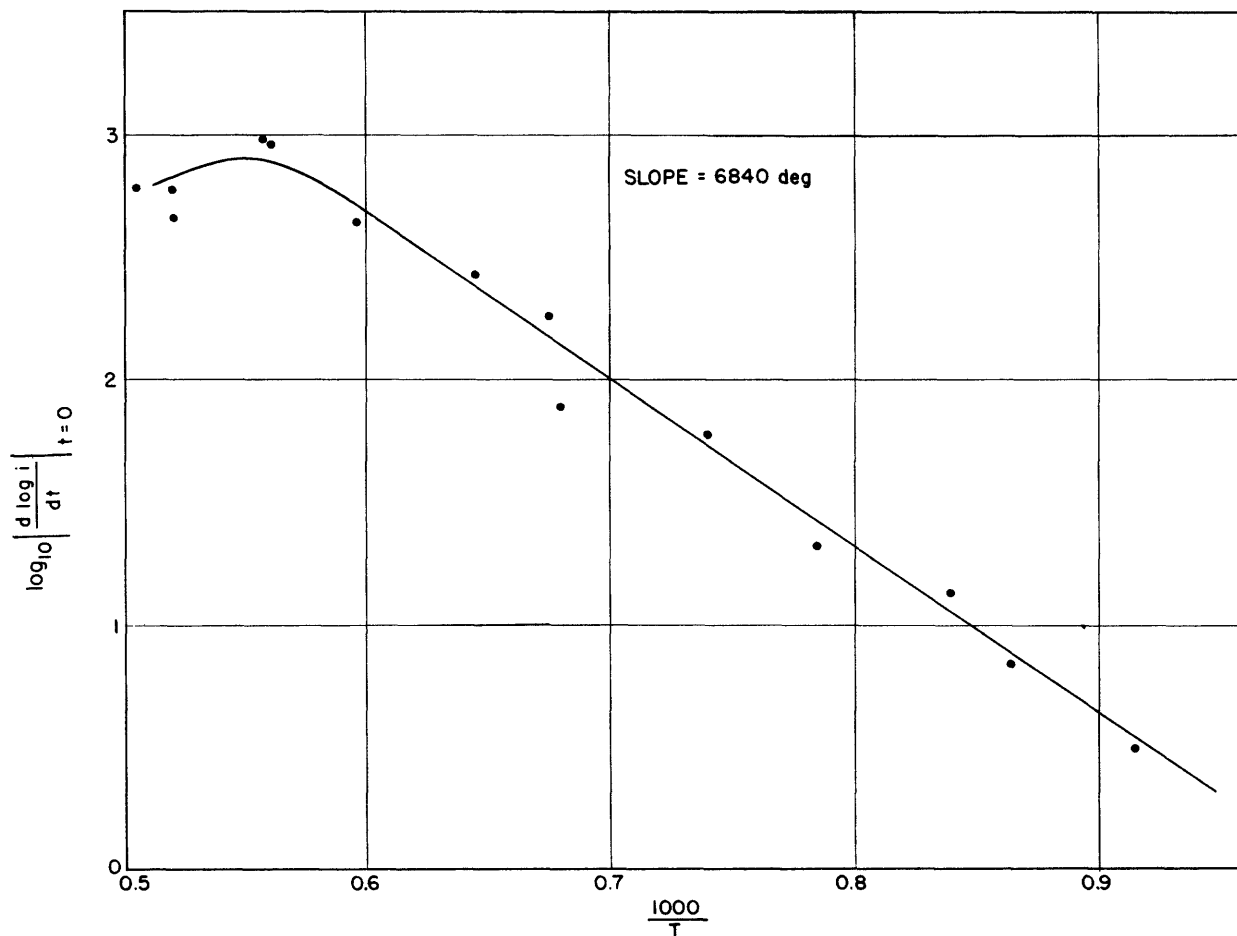


Fig. 17

curve is straight down to 1100°K. At the lower temperature the evaporation will be very slow. The slope of this line corresponds then to the heat of diffusion. The equation of this line is

$$\log_{10} \left| \frac{d(\log i)}{dt} \right|_{t=0} = \text{const.} - \frac{6840}{T} \quad (9)$$

giving the heat of diffusion to be 31900 cal/g-atom. At 1700°K the curve begins to bend because of the increased predominance of evaporation.

9. Concluding Remarks

The addition of tungsten powder has made the problem of heating very simple while retaining all the advantages of the sintered thorium cathodes, except for a somewhat higher work function. Thus, at 2040°K the maximum space-charge-limited emission at the bend of the curve in Fig. 3 is 0.9 amp/cm², whereas Hanley's data for thorium coated on tungsten give about 4 amp/cm². This difference is due to the fact that part of the surface is occupied by tungsten.

Our theory seems to give satisfactory explanations to the observed changes of activity with temperature. The probe measurements support our theory in confirming the evaporation of thorium. The estimated values of the heat of evaporation, 46000 cal/g-atom, is higher than the estimated value of heat of diffusion, 31900 cal/g-atom, and is lower than the known value of heat of reduction of thorium, 138000 cal/g-atom.¹ This is in accordance with the assumption of our theory.

It appears from our results that all thorium cathodes, where hot tungsten is in contact with thorium, should show changes of activity with temperature variation of the cathode. Indeed, Weinreich² observed that the emission of thorium coated on tungsten at 1800°K starting at a high value decayed with time, if the cathode had been previously flashed at a temperature above 2600°K. In this case, only by flashing at temperatures above 2600°K was considerable change brought about in the emission. It is significant, however, that as in our case the emission right after flashing (above 2600°K) was much higher than the equilibrium value at the lower temperature (1800°K). A thoriated tungsten filament would be completely deactivated at the flashing temperature and begin to activate at the lower temperature. As discussed above this is the case according to our theory, because the rate of thorium evaporation from thorium rises more slowly with temperature than the rate of evaporation from tungsten.

1. I. Langmuir, loc. cit.
 2. M. O. Weinreich, loc. cit.

Acknowledgments

The author wishes to thank Professor W. B. Nottingham for many discussions. He wishes also to acknowledge his indebtedness to Professor S. T. Martin for interest and help in carrying out this work, which was a part of a project under his direction.

